Engineering Structures 132 (2017) 87–97

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Three-dimensional progressive collapse analysis of reinforced concrete frame structures subjected to sequential column removal

Amir Hossein Arshian *, Guido Morgenthal

Institute of Modelling and Simulation of Structures, Bauhaus University Weimar, 99423 Weimar, Germany

ARTICLE INFO

Article history:
Received 29 April 2016
Revised 19 August 2016
Accepted 7 November 2016

Keywords:
Progressive collapse analysis
Sequential column removal
Nonlinear dynamic analysis
Reinforced concrete frames
Fiber-based modeling
Compressive arching action
Catenary action

ABSTRACT

In the last decade, a great care is exercised in progressive collapse analysis of structures to avoid the catastrophic consequences of such a system-level problem. The majority of the previous research works dealt with the quantification of resisting mechanisms such as the compressive arching action using two-dimensional frameworks. The three-dimensional (3D) studies are also limited to considering the initial damage as instantaneous removal of one or simultaneous removal of multiple supporting elements. This paper studies the 3D nonlinear dynamic response of reinforced concrete structures subjected to sequential column removal scenarios. A sequential nonlinear time-history analysis algorithm alongside with a macro modeling approach is utilized to predict the dynamic redistribution of the gravity loads. The efficiency of such a numerical framework is verified through comparison of computational results with the available experimental data from a past 3D half-scale test. Good agreement is observed for the global and for the local response quantities. Furthermore, a practical strengthening technique is applied into the computational model of the structural system for artificially activating the catenary mechanism. Analysis results show that strengthening of peripheral beams with externally bonded steel plates significantly increases the rotational ductility at beam-sections and in turn, enables the damaged structure to accommodate larger deformations. Finally, the influence of the removal sequence on the 3D force redistribution mechanism is investigated. Permanent plastic deformations and maximum sectional forces of a sequential removal scenario are found to be larger on average compared with those obtained from an at-once removal scenario. It is demonstrated that the time-lag between the column removals considerably affects the 3D redistribution of gravity loads, and shall not be neglected in case of considering an extreme initial damage.

1. Introduction

The catastrophic collapse such as those of the Ronan Point apartment building in 1968, the Alfred P. Murrah Federal Building in 1995 and the World Trade Center (WTC) towers on 11 September 2001 prompted the research communities to explicitly address such a system-level problem. Progressive collapse indicates a situation where failure of primary elements spread from element to element resulting in the collapse of the entire structure or a large part of it [1]. Progressive collapse guidelines such as [2,3] propose two general approaches of Direct Design and Indirect Design for mitigating the risk of progressive collapse. Among the proposed approaches, the threat independent alternate path (AP) method, which is a direct design approach is of researchers' interest. This method investigates the ability of the structure in redistributing of the gravity loads through bridging over the failed supporting elements.

In the last decade, a great care is exercised in the alternate path analysis of frame structures. Different numerical modeling approaches were studied. One of the simplest practiced modeling strategies is using elastic Bernoulli beam-column elements with lumped rigid-plastic hinges [4,5]. Such a modeling approach neglects the contribution of membrane actions of the bridging structural members in resisting progressive collapse. However, it has been well proved that the membrane actions significantly increase the collapse load in laterally restrained RC members [6–9]. In the last decade, the problem of compressive membrane action and catenary action has been significantly under research. However, the majority of previous experimental and numerical studies were mainly focused on either laterally restrained RC sub-assemblages [10–15] or 2D planar frames [16–18]. A two-dimensional study provides a relatively simple and efficient solution to the collapse resisting mechanisms such as the flexural

* Corresponding author.
E-mail address: amir.hossein.arshian@uni-weimar.de (A.H. Arshian).

http://dx.doi.org/10.1016/j.engstruct.2016.11.018
0141-0296/

action, the compressive membrane action and the catenary action. Nevertheless, apart from the ultimate-load bearing capacity of the structural members, the 3D investigation of the force redistribution mechanism is also crucial in evaluating the collapse-resistance of a given structural system. On the other hand, the majority of 3D studies are limited to considering the initial damage as instantaneous removal of one or simultaneous removal of multiple supporting elements, where little attention is paid to the influence of the failure-sequence on the force redistribution mechanism.

This paper aims to shed light on the influence of the removal sequence on the 3D force redistribution of the gravity loads assuming an extreme initial damage. A sequential nonlinear time-history analysis algorithm alongside with a macro modeling approach is utilized. Xiao et al.'s test [19] in which a 3D half-scale RC frame structure is subjected to sequential removal of its four columns is taken as the reference object. The efficiency of the applied numerical framework is verified for the global as well as for the local response quantities considering the entire range of the structural behavior from the elastic to the extreme plastic state, where the structure is identified as prone to collapse. Furthermore, a practical strengthening technique is applied into the computational model of the structural system for artificially activating the catenary mechanism. Peripheral beams are strengthened with externally bonded steel plates attached to the bottom of the beam-sections. The load-bearing capacity enhancement due to the development of catenary forces is comprehensively discussed. Finally, the influence of the removal sequence on the 3D force redistribution mechanism is investigated through a comparative study, where computational results are compared with an at-once removal scenario.

2. Analysis methodology for sequential removal scenarios

2.1. Overview

In an alternate path analysis, the aim is to investigate the ability of the structure in redistributing of the gravity loads to the undamaged bays. The proposed analytical approaches are typically using the linear static, nonlinear static, and nonlinear dynamic analyses. Although the linear static analysis approach is easy to be applied, it may not properly reflect the nonlinearity and the dynamic effects [20]. Usually, the nonlinear static procedure is preferred due to its simplicity compared with the nonlinear dynamic analysis procedure. In a nonlinear static procedure, the dynamic effects will be reflected using load increase factors such as those proposed by [21,22]. Nevertheless, the proposed load increase factors are mainly based on the single column removal assumption, which is not valid for the case of extreme initial damage. Thus, to have a clear understanding of force redistribution mechanism, particularly for the extreme events, use of nonlinear dynamic analysis approach is inevitable. As for considering an extreme initial damage, the simultaneous removal of multiple beam-column elements is already investigated by [23–25]. However, little attention is paid to the influence of the removal-sequence on the 3D force redistribution, where the redistribution of the gravity loads continuously changes its direction following each column removal. Contrary to the simultaneous removal strategy, the forces will be redistributed in an unfavorable asymmetric manner considering the time-lag between the column removals. That is, an at-once removal scenario does not necessarily yield a conservative solution to the problem of progressive collapse resistance for a given structural system, where a limited number of beam-column elements are failed as the direct or indirect consequence of an extreme loading scenario. This paper utilizes a sequential nonlinear time-history analysis algorithm using macro modeling approach for investigating the 3D force redistribution mechanism for the sequential removal scenarios.

The proposed numerical framework can be also implemented in robustness assessment of the structural systems. A comparable numerical framework for robustness assessment of the structural systems is the common used incremental-mass nonlinear dynamic analysis [4,26,27]. In an incremental-mass nonlinear dynamic analysis, the residual capacity of the damaged structure will be obtained with virtually increasing the gravity loads in an incremental time-history analysis. Although such an analysis approach predicts the behavior of the damaged zone from the elastic state to the dynamic instability state, the initial damage is limited to the prescribed local failure. On the contrary, a sequential-removal framework enables the analyst to robustly consider the propagation of failures. Thus, predicting the collapse extension is possible. Besides, there is no need to artificially increase the gravity loads using such a framework, which is more realistic in terms of structural loading.

2.2. Finite element modeling approach

Fiber-based modeling approach provides a reliable solution to the distributed plasticity problem in frame elements. Such a modeling technique has been widely used in predicting the ultimate load-bearing capacity of frame elements considering the flexural-axial deformation interactions [17,25,26,28]. As for the element-formulation, the displacement-based element (DBE) and the force-based element (FBE) formulations are typically implemented. In the conventional DBE formulation, the solution is derived based on discretization of the displacement fields of the element using approximate interpolation functions. However, a FBE yields the solution using exact force interpolation functions. Thus, a FBE provides a robust solution as only numerical integration error is involved [29]. Nevertheless, facing extreme convergence problems is very probable using FBEs, particularly in softening problems such as progressive collapse analysis. Thus, a great care must be exercised in the finite-element discretization as well as in the solution algorithm using FBE formulation. A comprehensive discussion on the efficiency of using DBE and FBE formulations in progressive collapse analysis of RC frame structures can be found in Arshian et al. [26].

As for the planar elements, the nonlinear multi-layered modeling approach is widely used to account for the development of nonlinear membrane forces [30–32]. In a multi-layered shell element, using the plane-section assumption, strain at each layer will be obtained according to the axial strain and curvature of the middle layer. Using corresponding constitutive material models, the subsequent stresses at each layer will be calculated then. The planar constitutive model for concrete which is based on the concept of damage mechanics and smeared crack model includes the nonlinear behavior of concrete such as cracking, crushing and aggregate interlocking. The shear stiffness reduction following the cracking of concrete layers is also accounted for using the so called shear retention factor [33]. The nonlinear behavior of reinforcing steels is also reflected in the uniaxial stress-strain relationship of smeared steel layers.

2.3. Analysis methodology

The analysis procedure for a sequential column removal scenario is schematically depicted in Fig. 1. Finding the equilibrium forces (P_1, V_1, M_1) for the first removal through a finite element analysis of the undamaged structure, the gravity loads G alongside with the equilibrium forces are applied into a damaged finite element model of the structural system. While the gravity loads remain constant, the equilibrium forces drop to zero at $t = t_1$, in